

Naval Postgraduate School Support Task

March 2000

Prepared by:

*Schafer Corporation
1901 N. Fort Myer Drive
Suite 800
Arlington, VA 22209
703/558-7900*

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**Final Report – Naval Research Laboratory
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Naval Postgraduate School Support Task

The Naval Postgraduate School (NPS) provided funds for Schafer Corporation to provide the Physics Department at the Naval Postgraduate School information and material for curriculum development.

The purpose of this task was to provide lecturing and curriculum development support, as needed, to the Naval Postgraduate School's Physics Department/Weapons Curriculum in the area of High Energy Laser systems.

A Schafer consultant performed all of the work and updated some previous lecture materials on megawatt-class high energy lasers and on the current status of DoD HEL programs. This was presented to the faculty and graduate students at the Naval Postgraduate School in a colloquium. The lecture covered the basic elements of how an HEL weapon works, described the types of lasers which have achieved high average power, showed results from a few MIRACL/SLBD tests, showed top-level budgets for DoD's HEL programs over the past three decades, and briefly described the Airborne Laser Program, the Space Based Laser Program, and THEL. While at NPS, work was initiated with faculty members on developing a course outline in Directed Energy.

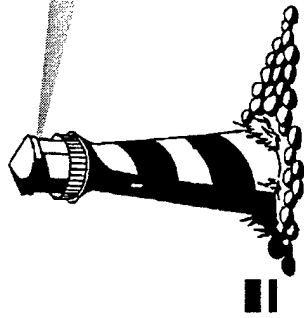
NPS Weapon System faculty are developing a curriculum called *System Engineering Integration* for Navy Unrestricted Line Officers. The stated goal is "...to enable the student to exploit emerging technologies to achieve war-fighting advantages." Our nation's approach to winning conflicts through technological superiority requires Naval Officers to function using highly complex, integrated weapon systems. This necessitates, however, a firm grounding in math, physics and engineering disciplines to understand weapon system limitations and to obtain full benefit from their capabilities.

As part of the activity, support was provided by participation in a two-day meeting at Johns Hopkins Applied Physics Lab with faculty members from the Naval Postgraduate School and a few senior folks from APL. The purposes of the meeting were to discuss course content ideas and to gain an understanding from APL of the chronology of anti-air defense. The latter led to the obvious conclusion that the netting of sensors and weapons within and across ships along with the consolidation of command and control is essential to defeat today's anti-ship missiles. Systems engineering is at the core of the effort. Various war-gaming tools, available at APL, were discussed as possible student exercises. Considerable discussion and debate ensued on the relative merits of various courses in the basics of science/engineering versus survey courses in system engineering related topics.

At the request of the Naval Postgraduate School, a letter was prepared for the Physics Department Chairman describing the working relationship which existed in the past between the Physics Department and the Navy's HEL program at NAVSEA and later at SPAWAR. Cooperative efforts included support of graduate student and faculty research by the HEL program, guest lectures to the students by HEL program experts, and advice from the faculty on technical issues facing the program office.

Attached is Appendix A, the briefing material on Lasers with Megawatt Average Potential. Other information provided to NPS had budget information which is not appropriate for general dissemination and was provided under separate cover.

Appendix A

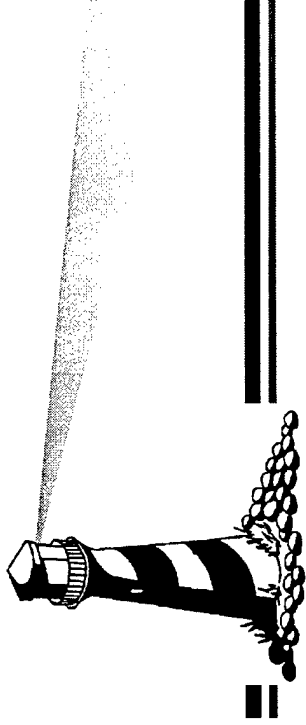


High Energy Laser Candidates

Overview of Lasers with Megawatt Average Power Potential

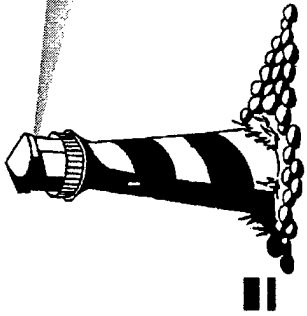
March 1998

**John R. Albertine
109 Kingswood Road
Annapolis, MD 21401
(410) 571-6772
fax-6773
albertij@erols.com**

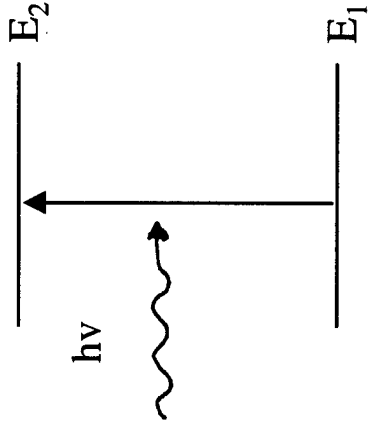


Outline

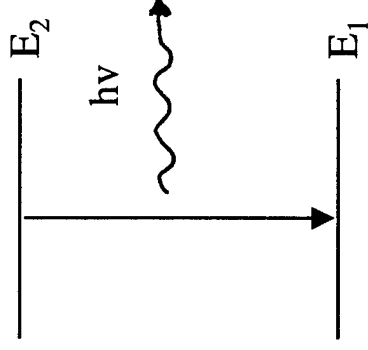
- What is a Laser?
- Desirable weapon laser characteristics
- High Power Laser candidates
 - Gas
 - Chemical
 - Solid State
 - Free Electron



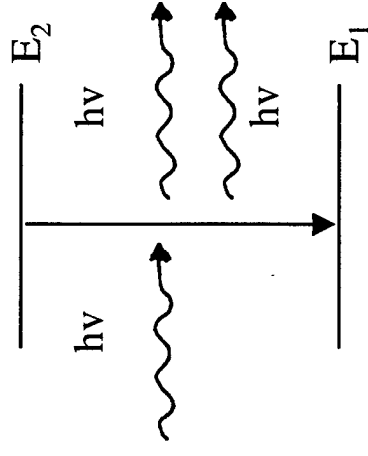
EM Wave / Material Interactions



absorption
(atoms initially at E_1)

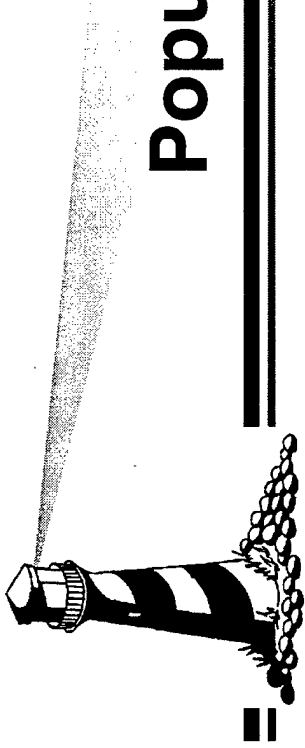


spontaneous emission
(atoms initially at E_2)

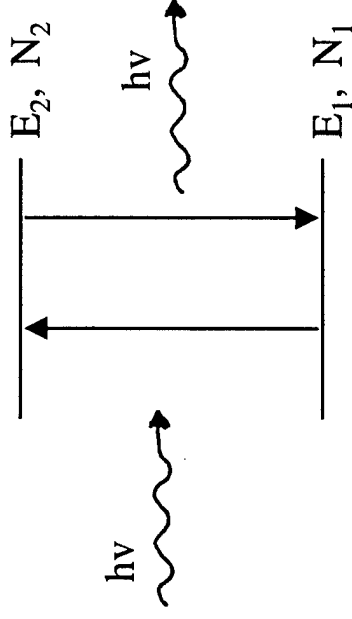


stimulated emission
(atoms initially at E_2)

- unphased photons
- random directions
- forced by incident em wave
- in phase
- same direction

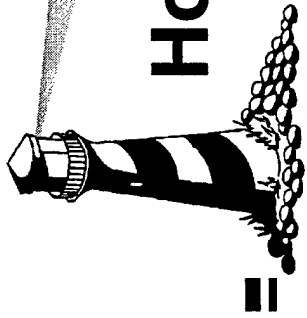


Population Inversion



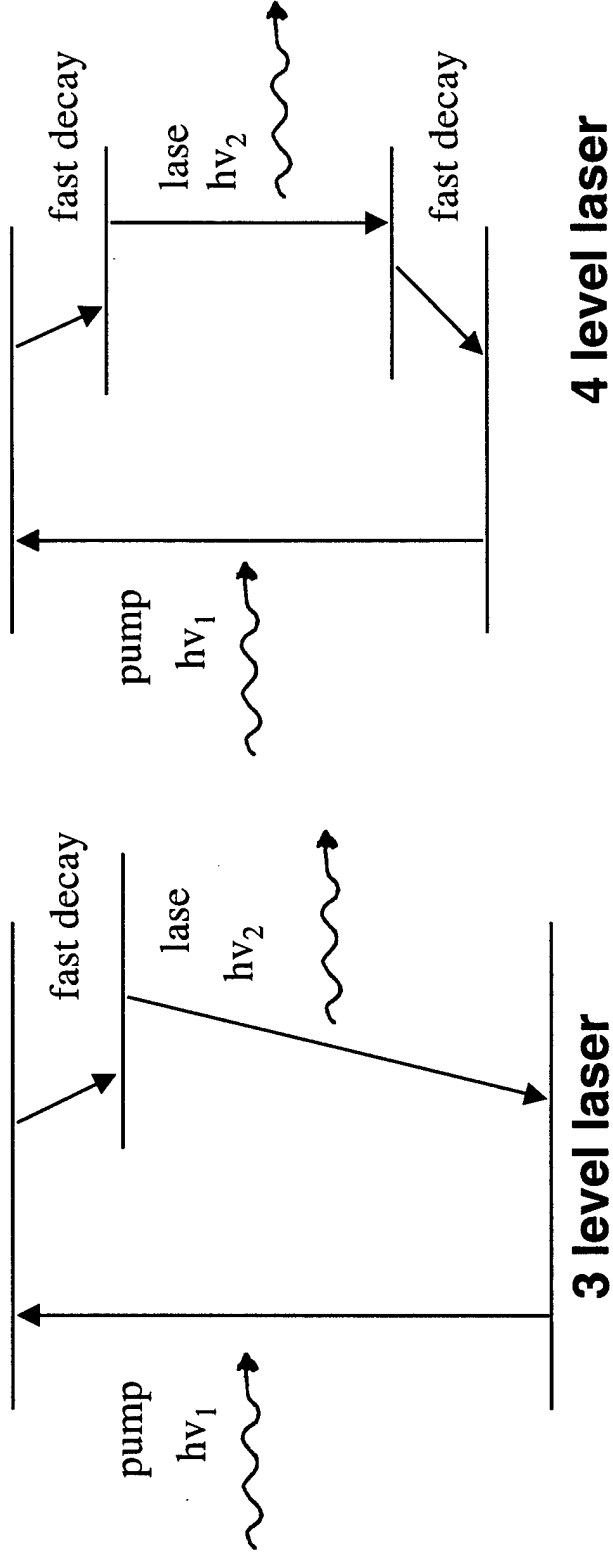
for materials above absolute zero
& in thermal equilibrium

- $N_2 < N_1$ (Boltzmann distribution)
 - material absorbs when irradiated at $\lambda = h\nu$
- if $N_2 > N_1$
- have a population inversion
 - acts as amplifier at $\lambda = h\nu$
 - Light Amplification by Stimulated Emission of Radiation (Laser)

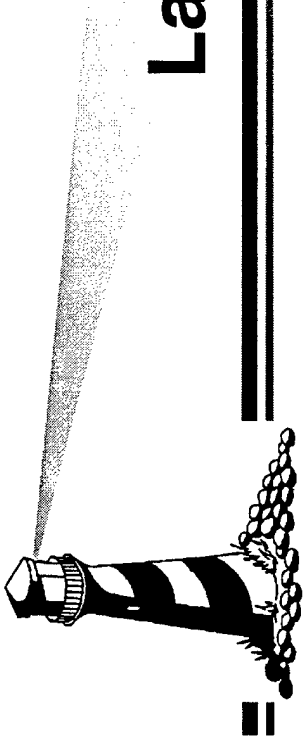


How to Achieve Population Inversion?

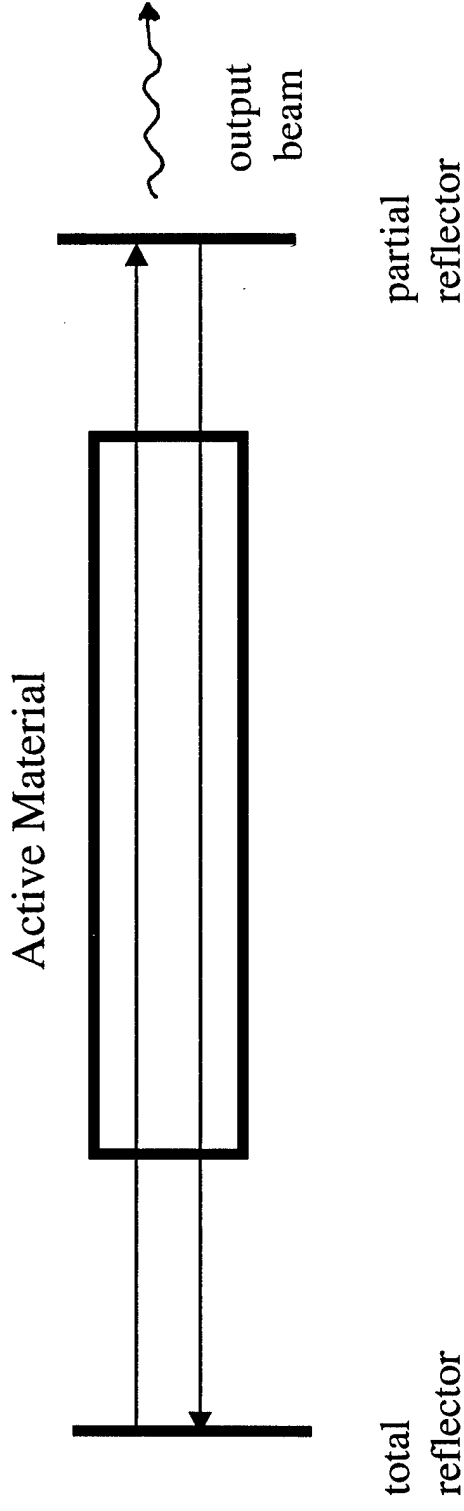
- Can not obtain population inversion in 2 level material
- rate (E_1 to E_2) = rate (E_2 to E_1) can't win



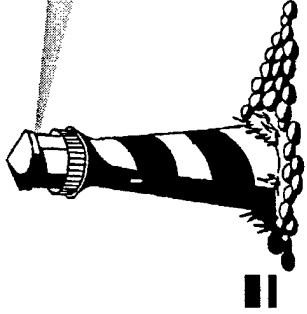
- note: non-lasing decays generate heat!



Laser Oscillator

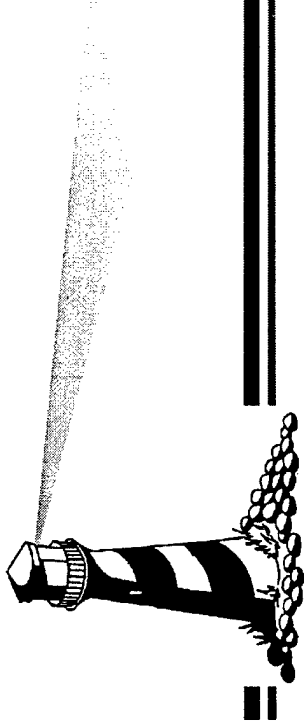


- Introduce positive feedback to amplifier
- Round trip Gain > Round trip Losses
- Builds from Spontaneous Emission



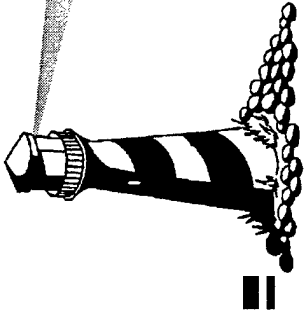
Desirable HEL Weapon Characteristics

- ~ Megawatt average power at target
- Long run time (10s - 100s seconds)
 - Efficient
- Intense HEL spot on target
 - Small enough not to waste energy
 - Large enough to inflict damage
 - Good thermal management (constant spot size)
- Useful Wavelength
 - Propagate efficiently through path (absorption & scatter)
 - Require reasonable size telescope ($0 \sim R \lambda / D$)
- Compact
- User Friendly



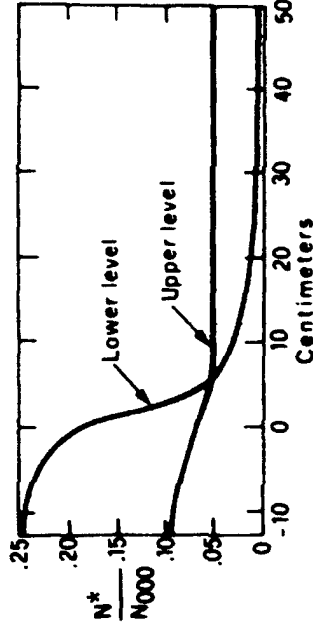
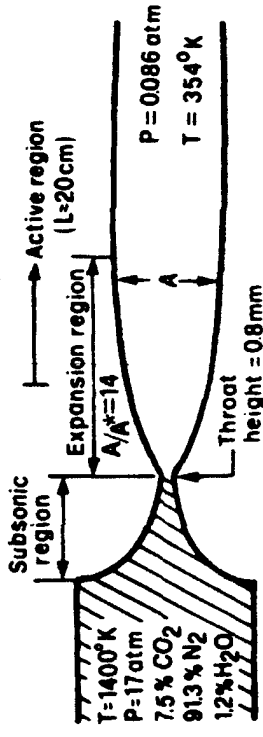
Gas Lasers

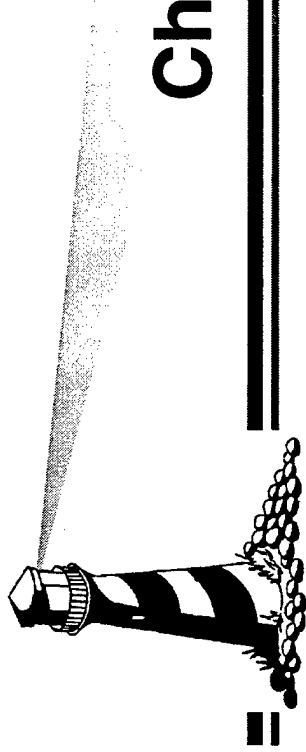
- Low pressure cavities (usually flowing gas)
- Narrow pump bands
- Not suitable for optical pumping
- Pumped
 - Electric Discharge (EDL)
 - Gas Dynamic Expansion (GDL)
 - Optically using another laser
- Lasing
 - Between vibrational ground state levels (long IR $\lambda > 5$ microns)
 - Between vibronic levels of different electronic states (uv excimers)



CO₂ Gas Dynamic Laser

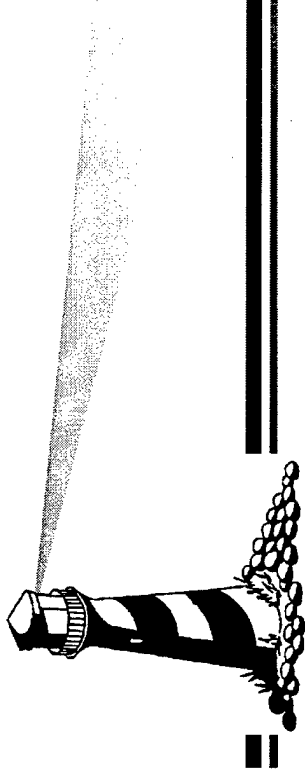
- **First High Average Power Lasers**
- **near MW in 1970s**
- **Combustion Driven**
 - Rapid expansion of hot gas mixture with CO₂ & N₂
 - Resonant energy transfer from N₂ to CO₂
 - 10.6 or 9.6 micron lasing
 - Heat exhausted from laser
- **Poor atmospheric transmission**



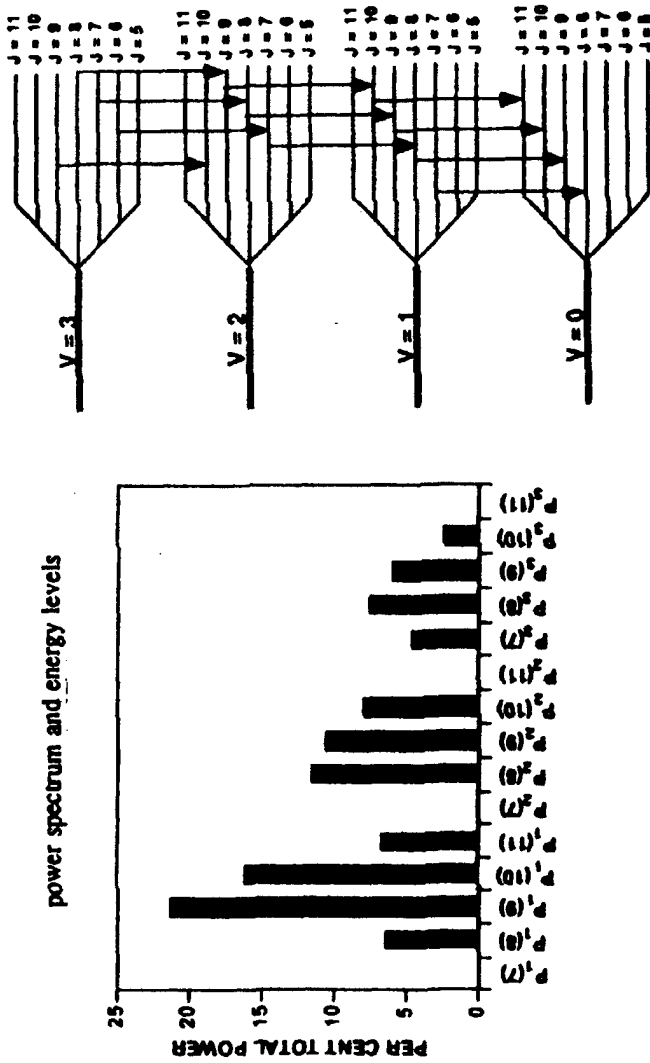


Chemical Lasers

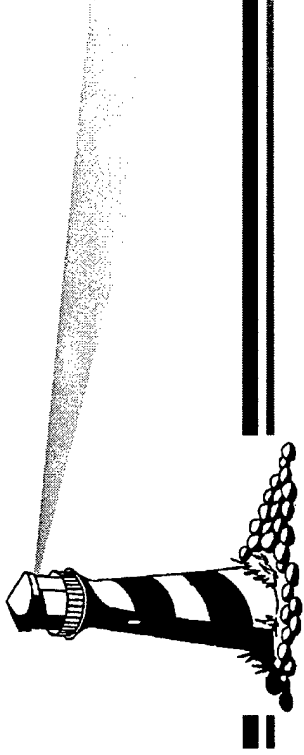
- Population inversion produced directly by exothermic chemical reaction
 - Electron Discharge (electric arc)
 - Photolysis (flash pumped)
 - Combustion Driven
- Second laser type to reach MW (MIRACL -1980)
- Examples
 - $\text{H}_2 + \text{F} \rightarrow \text{HF}^* + \text{H}$ (HF lasing at 2.6 to 2.9u)
 - $\text{D}_2 + \text{F} \rightarrow \text{DF}^* + \text{D}$ (DF lasing at 3.7 to 4u)
- Very high active medium gain
- Heat exhausted from laser



MIRACL

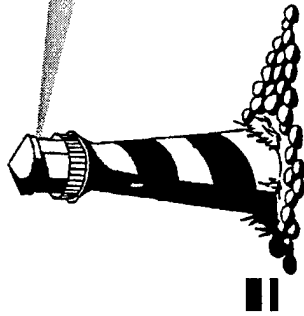


- Combustion Driven DF* Chemical Laser
- First Lased 1980 - MW class, still DoD's largest
- Built for Navy SeaLite program
- Good atmospheric propagation



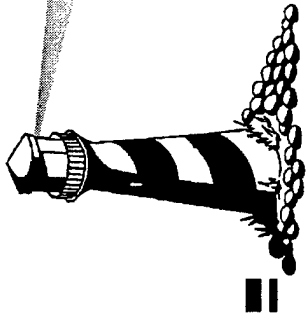
ALPHA

- Combustion Driven HF* Chemical Laser
(2.8 microns)
- First Lased in 1987, lower power than MIRACL
- Built for SDI Space Based Laser program
- No atmospheric propagation - space only
- Cylindrical gain generator, torroidal resonator
- Concept scalable to much higher power than
MIRACL

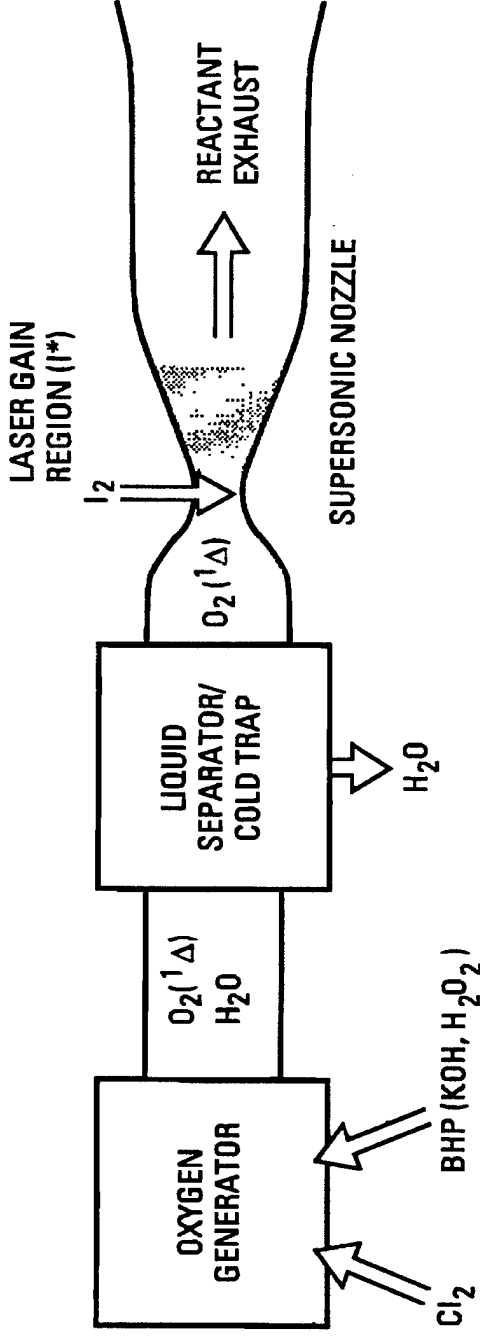


Chemical Oxygen Iodine Laser (COIL)

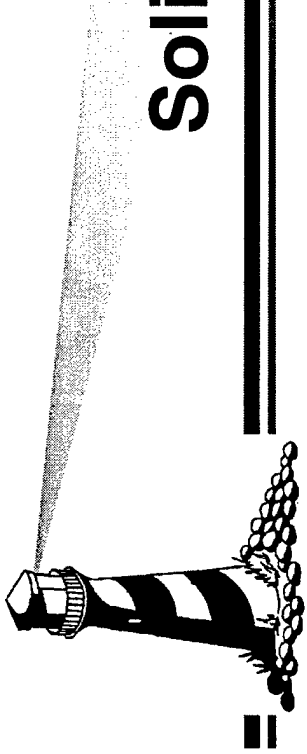
- Developed by Air Force for airplane based use
- 100kw demonstrated
- Good atmospheric propagation
 - Absorption similar to DF
 - Higher scatter due to shorter wavelength
- First chemical laser to use electronic transition
 - Iodine pumped through resonant transfer from metastable O_2^*
 - Lasing between fine structure levels of Iodine atom.
($I^* 2p_{1/2} \rightarrow I^* 2p_{3/2}$)
- Heat generated in O_2 generator, easily removed.



Chemical Oxygen Iodine Laser

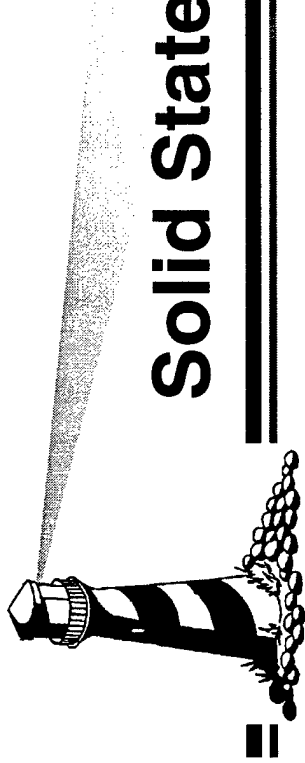


- Cl_2 reacts with basic hydrogen peroxide (BHP)
- $\text{O}_2(^1\Delta)$ is formed
- $\text{O}_2(^1\Delta)$ dissociates I_2 via two step mechanism
- $\text{O}_2(^1\Delta)$ transfers energy to I to produce I^*
- Slow deactivation rates relative to HF/DF lasers
- I^* lases at 1.315 microns
- Single line operation eases optical coupling
- Excellent atmospheric transmission
- Long optical mode length ~ 10 cm
- Potential for both pulsed and cw operation



Solid State Lasers

- **Active medium**
 - Insulating Crystal (ex: Yttrium Aluminum Garnet - YAG) or Glass host
 - Impurity ions deposited in host (ex: Nd or Yb)
- **Lase around 1 micron**
- **Optically pumped with flashlamps or diodes**
- **Can generate high peak powers**
- **Average power limited by ability to extract heat from host**
- **Wavelengths propagate extremely well in clear weather**
 - Low absorption
 - Higher scattering in haze/fog



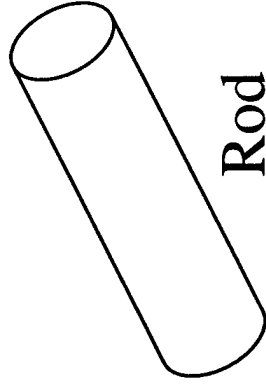
Solid State Laser Design Issues

■ Goals

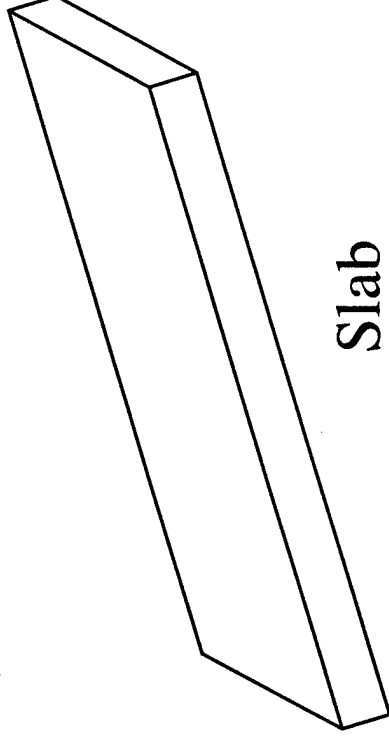
- Higher Average Power (need larger gain medium volume)
- Good Beam Quality (need efficient heat extraction)
- Long Run time (need efficient heat extraction)

■ Laser Requirements

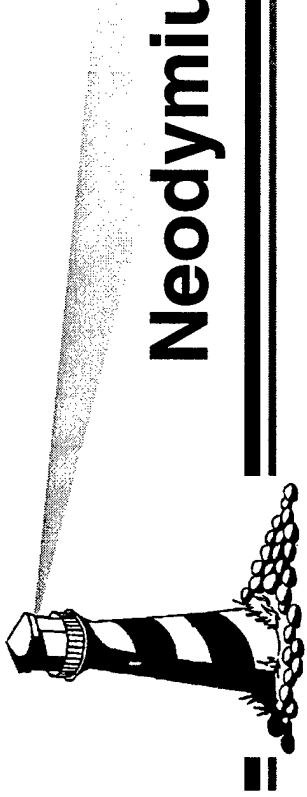
- Optical Pumping of Gain Medium (flash lamp or diode)
- Cooling (efficient heat extraction)
- Resonator/Gain Medium with good optical quality



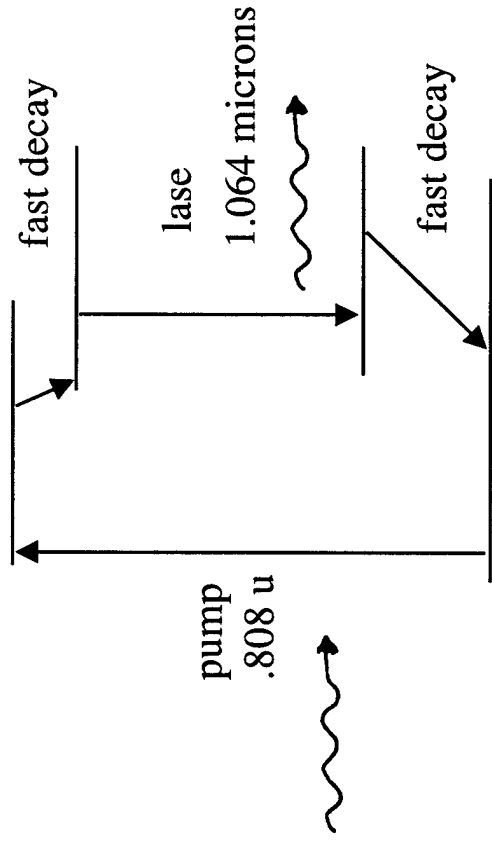
Rod



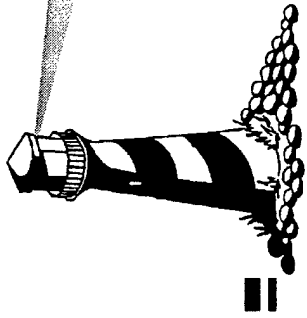
Slab



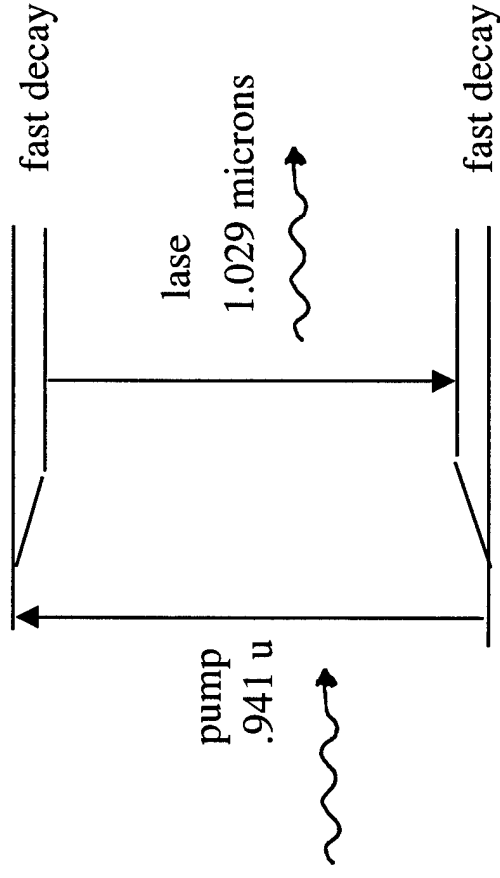
Neodymium (Nd) :YAG laser



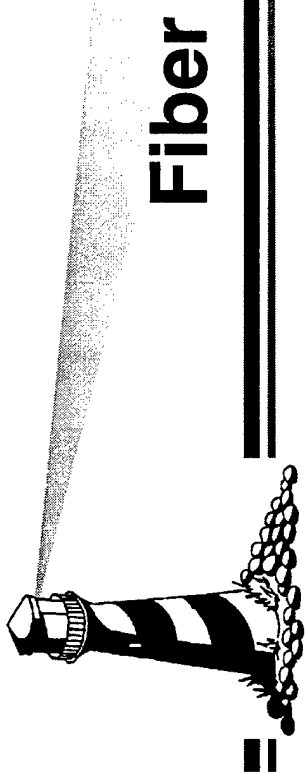
- 4nm absorption linewidth
- 24% heating from quantum loss
- Saturation intensity $\sim 3\text{kw/cm}^2$ ($\sim 2\%$ dopant)
- Max average power potential - few hundred kw
- Can't run continuous - unable to extract heat fast enough



Ytterbium (Yb) :YAG Lasers



- 18nm absorption line width
- InGaAs pump laser diodes at .941u
- 8.6% heating from quantum loss
- Saturation intensity ~ 9.7kw/cm² (~25% dopant)
- Max average power potential - perhaps MW
- Can run continuous



Fiber Optic Amplifier

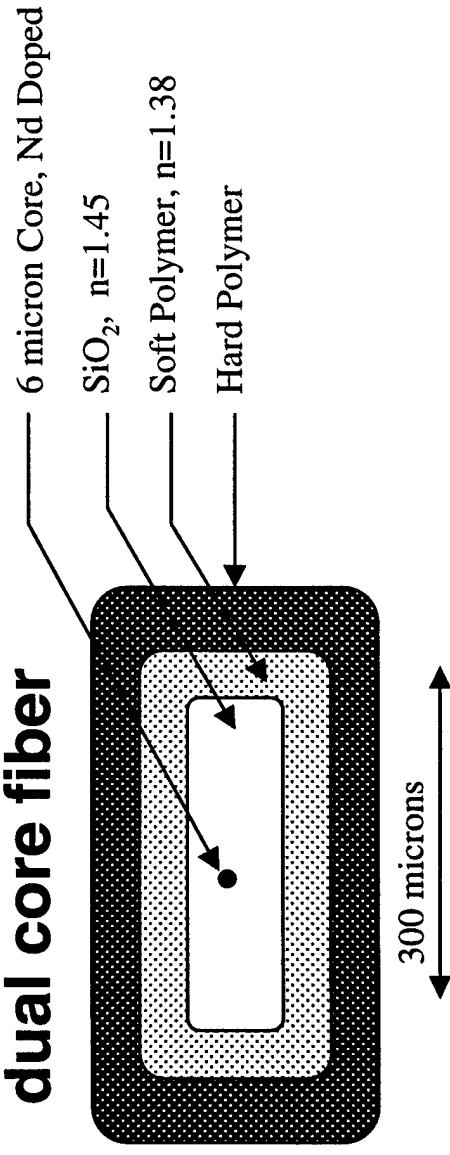
■ Active Medium

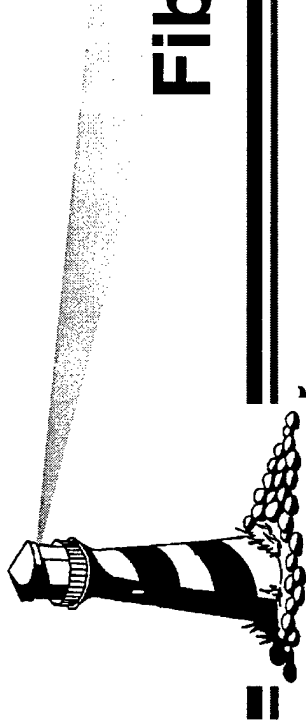
- Stretch Nd:YAG into long thin fiber
- Easy heat removal (large surface area/unit volume)

■ Pump

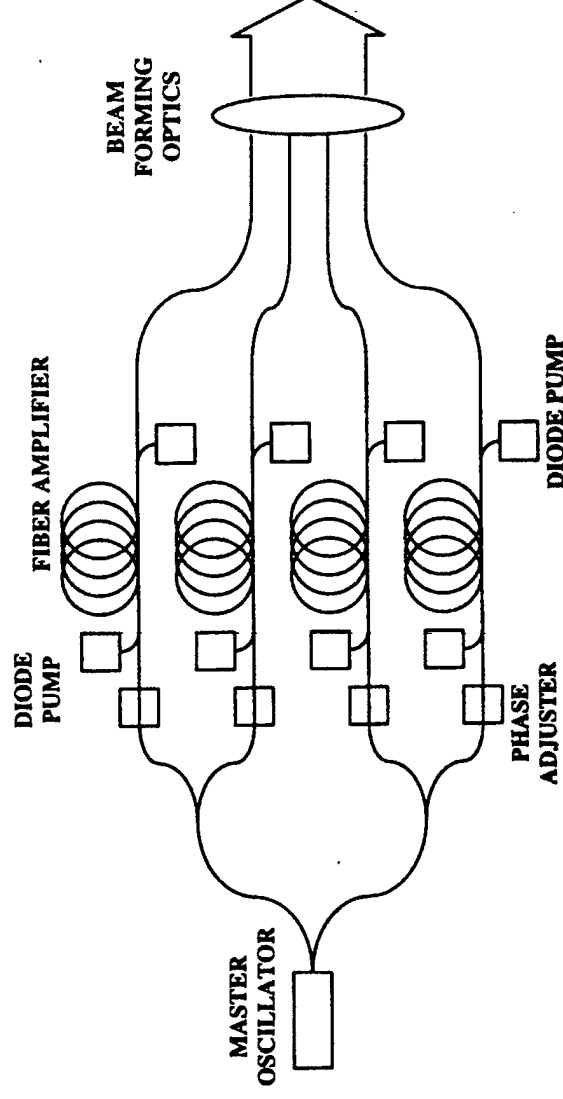
- Surround fiber with optically transparent jacket
- End pump optical jacket with diode lasers
- Active medium pumped along entire length

dual core fiber



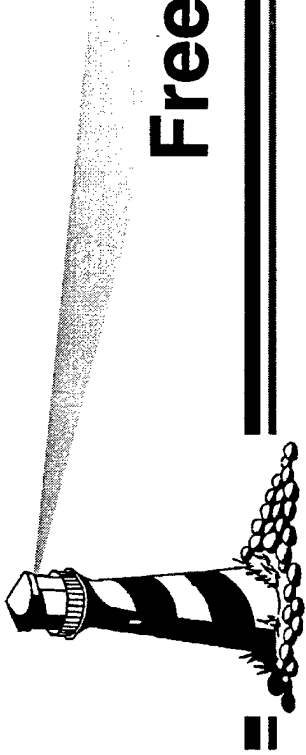


Fiber Optic MOPA



■ Master Oscillator, Power Amplifier Configuration

- 100 watt amplifier demonstrated
- Each amplifier slaved to common oscillator
- In principle can be scaled without limit
- Parts count linear with power
- Challenge is in phasing amplifier outputs



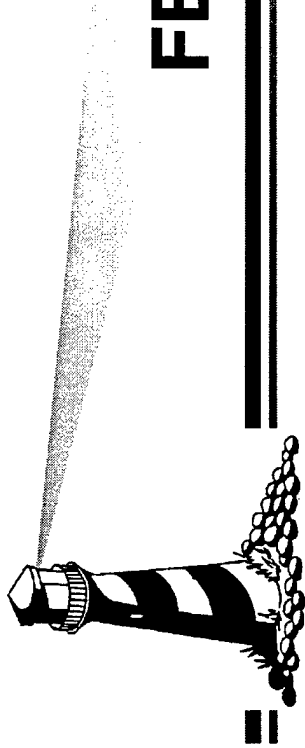
Free Electron Laser

■ Totally different concept - not a classical laser

- Can be scaled to very high power
- Design can be tuned to desired wavelength for optimum atmospheric transmission
- Extremely complex, radiation problems
- Parts count almost independent of power

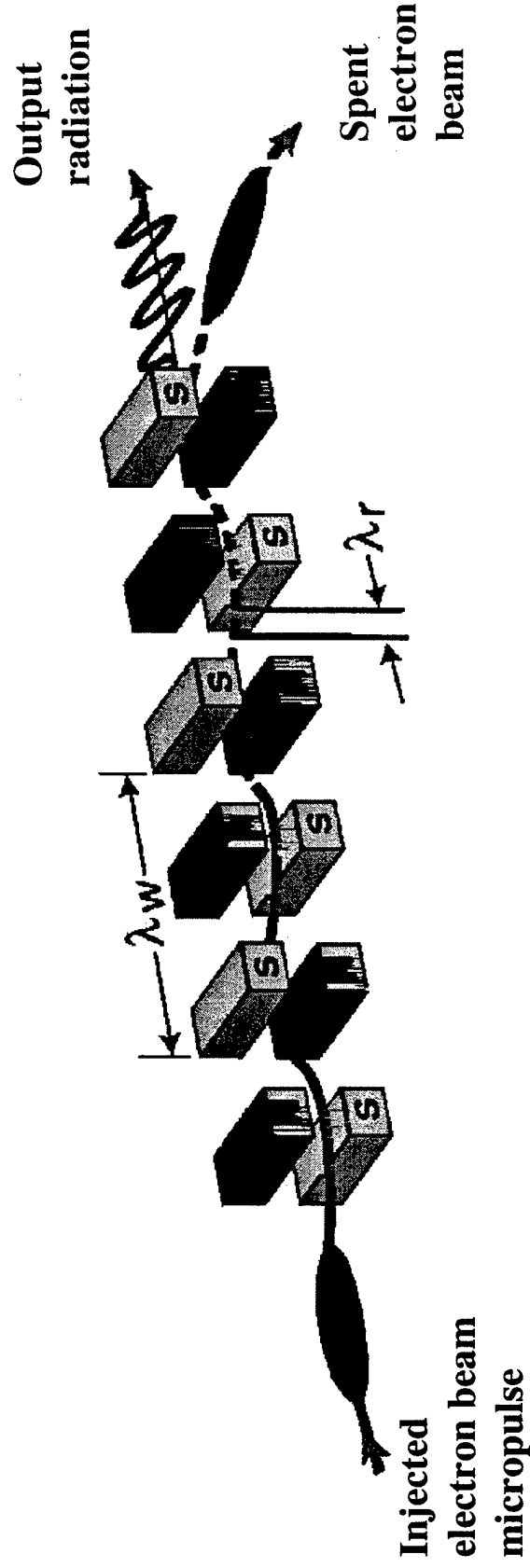
■ Implementation

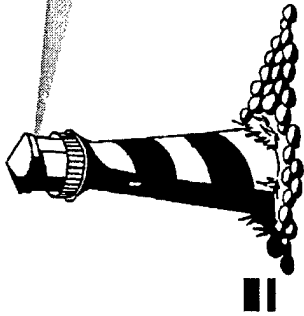
- Generate & Accelerate high quality electron beam bunches to relativistic velocities
- Laterally wiggle electron beam to produce photons
- Wrap resonator around optical beam
- 10 watts - highest average power to-date
- 1kw - hardware built, now being checked out
- MW concepts exist



FEL Interaction

- Electron beam undulates in wiggler and bunches at optical wavelength
- Optical radiation is amplified at the double-Doppler-shifted wavelength of the wiggler





Summary

- **MW average power HELs have been built**
 - Large & not at optimum wavelengths for Navy
 - DF (3.8u) usable with sufficient crosswind
- **Robust MW source needed at ~ 1u windows.**
 - No gas/chemical laser candidates on horizon
 - Solid state lasers offer most attractive solution
 - ◆ Yb:YAG - thermal management & BQ problems
 - ◆ fiber laser - beam combining & high intensity problems
 - ◆ both - pump diode cost and reliability
- **FEL**
 - ◆ highest probability of achieving MWs
 - ◆ Large, expensive & complex
 - ◆ radiation hazard